WIDE BAND ANALOG SIGNAL PROPAGATION IN A FIBER OPTIC SYSTEM

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THESIS

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ABSTRACT

State of the art advances in fiber optics have reached the point at which modulated light signals can be transmitted by means of a fiber optic bundle and subsequently detected. A system capable of modulating a light emitting diode with wide band analog signals, transmission through a fiber optic bundle, and subsequent detection is investigated.

Tests are conducted to determine frequency response, linear dynamic range, saturation levels, minimum discernible signal, noise figure, and spectrum characteristics of the system.

As a result of the investigation, it is determined that the system is suitable for transmission of information to tape recorders from receiver systems and is capable of other analog information applications where signal frequencies do not exceed seven megahertz.

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I. INTRODUCTION

The transmission of light through a medium is known to obey the same laws of physics as the transmission of electromagnetic energy such as radio or radar transmissions and, just as microwave radar signals can be propagated through a waveguide, light will propagate similarly through a suitable waveguide.

Light frequencies are much higher on the electromagnetic spectrum than are signals associated with radar transmissions and therefore are of much shorter wavelength than radar signals.

In the propagation of electromagnetic energy through a waveguide, the wavelength of the energy determines the minimum physical size of the waveguide. As the frequency increases with a corresponding decrease in wavelength, the physical dimensions of the waveguide can become smaller and waves can still propagate. At lower frequencies, the dimensions of the waveguide required to efficiently propagate the energy become prohibitively large both economically and practically.

At the other end of the spectrum, however, at the frequencies of light with their correspondingly small wavelength, the physical size of the waveguides becomes very small. It would be extremely difficult to fabricate conventional waveguides on this small a scale.

Present technology in the area of fiber optics has reached the point at which glass fibers can be produced economically with relatively low dielectric losses and within the tolerances required for the efficient transmission of light at specific wavelengths. Several methods and techniques for the transfer of digital information via a fiber optic

link have been demonstrated and are being used in some instances [Ref. 1].

Because optical fibers can be bent and routed in a manner similar to a wire conductor with no significant attenuation of energy, their use in shipboard, and airborne, and other military applications, as well as in commercial applications offers a promising future.

Although much effort has been expended in devising and improving techniques for digital signal propagation through optical fibers, comparatively little effort has gone into analog applications. Efficient propagation of analog signals through optical fibers offers an attractive alternative to the present use of conductive metal cables presently used in most military applications.

The advantages of optical fibers over conventional transmission media are many. Optical fibers are smaller in size, weigh less, and are much less susceptible to EMI (electromagnetic interference) and cross-talk than are metallic conductors. In addition, optical fibers of glass construction have a higher resistance to heat and have a higher tensile strength than do metallic conductors. Because there is no electrical connection between the ends of the fiber, ground loops are eliminated and almost total isolation is obtained between the input and output of an optical system.

Optical fibers presently available propagate light most efficiently in the infrared region of the electromagnetic spectrum in the vicinity of nine thousand angstroms in wavelength. Infrared light emitting diodes and photodiodes are available that lend themselves readily to modulation and detection techniques in the infrared region. It seems reasonable then, that an investigation into the possibility of broad band analog propagation of signals through a fiber optic medium would be productive.

The investigation focuses upon the effectiveness of propagating an electromagnetic signal through an optical fiber using conventional means of modulating a light emitting diode and subsequent detection of the signal with a readily available commercial photodetector and preamplifier unit. The investigation is undertaken with two principal applications in mind.

One possible application is that of coupling information from a radio receiver or signal source to a tape recorder. The use of fiber optics in this application appears attractive in that isolation between the signal source and tape recorder is very high with the subsequent elimination of ground loops. Interconnection between radio receivers and tape recorders in shipboard and airborne systems have presented many problems in the past.

The second application to be considered is that of coupling signal energy from a receiving antenna on the mast of a ship to the radio receiver in the ship. The use of a fiber optic transmission line would eliminate cross-talk between signal channels, electromagnetic interference from other shipboard radars and transmitters, and would provide isolation between antenna and receiver. The use of a fixed array of antennas, each with its own fiber optic link to the receiver, and interferometry techniques could also lend itself well to radio direction finding applications without the disadvantages inherent with a rotating D-F antenna, i.e., mechanical equipment failures and alignment problems. It would be very desirable to have such a system in the two to thirty two megahertz frequency range. A major portion of long haul communications takes place in this range and up to the present there has been

little progress in the area of adequate and inexpensive shipboard direction finding techniques at these frequencies.

Other possible applications in which fiber optics may offer distinct advantages are usage in intra-ship or intra-aircraft communications and in secure teletype or secure radio spaces at military installations.

II. BACKGROUND

The basic components of the system under investigation were 1) the modulating circuit utilizing a light emitting diode as the output element, 2) the optical fiber used to transmit the signal, and 3) the photodiode and preamplifier combination used to detect the signal after transmission through the optical fiber.

A. LIGHT EMITTING DIODE CHARACTERISTICS AND PROPERTIES

A light emitting diode is a device which emits light in a manner which is proportional to the amount of current passing through it. Recombination of electrons and holes takes place whenever current is passed through a p-n junction. When the carriers are separated by the equivalent of the semi-conductor band gap energy or greater, the excess energy is removed by radiative recombination (emission of a photon), or the energy is emitted as heat. Photon emission due to recombination radiation is responsible for the observed light obtained from light emitting diodes. In forward bias, the radiation is peaked around the band gap energy. Certain semiconductor compounds such as Gallium Arsenide (GaAs) have a much higher probability of radiative recombination than do other semiconductor materials thus resulting in a much higher efficiency of photons, or light, output. The wavelengths of light emitted from Gallium Arsenide vary from .65 microns to about 3 microns dependent upon the mixture of compounds and the doping levels. Characteristics of the light emitting diodes also depend upon the method by which the p-n junction is produced. Two primary methods by which the junctions are produced are the diffused junction method and the solution

grown junction method. It is known that the diffused junction devices are more suitable for modulating than are the grown junction devices. The grown junction devices are generally more suitable to applications as indicators and in systems which a light interrupt or a light on/light off signal is required at low rates.

The theoretical maximum rate [Ref. 2] at which light emitting diodes may be modulated is

$$f_m = \frac{1}{2\,\tau_c}$$

where f_m is the ultimate frequency of modulation and τ_c is the carrier lifetime of the semiconductor material. Carrier lifetime in Gallium Arsenide is approximately 10^{-8} seconds [Ref. 3] depending upon the amount of doping material and the method of manufacturing the junction.

Assuming this value of carrier lifetime, the ultimate frequency of modulation for a Gallium Arsenide light emitting diode is 50 megahertz. The rate at which the light emitting diode can be modulated in a given system is also affected by the modulator circuitry.

Pure Gallium Arsenide emits light in a 300-400 Angstrom range centered in the 9000-9300 Angstrom range [Ref. 2]. Doping the Gallium Arsenide with Phosphorous or Aluminum shifts the emission spectra into the visible range, however, these light emitting diodes are only about 10 per cent as efficient as the pure Gallium Arsenide devices.

The ability to dissipate heat is another factor which affects the efficiency of light emitting diodes. At low power levels, heat dissipation has a lesser effect upon the device performance and cw power output is a linear function of input power. As the power level is increased,

the light emitting diode output tends to be non-linear because of an increase in non-radiative recombinations and an increase in reabsorption of emitted radiation.

Light emission of a light emitting diode has no preferred direction and hence it becomes necessary to use specially designed headers or a dome type lens to direct the light output.

Since light emitting diodes are current sensitive devices, almost any modulation scheme which produces current variations proportional to the input signal is suitable as long as there is enough drive current to operate the LED.

B. OPTICAL FIBER CHARACTERISTICS AND PROPERTIES

Atmospheric optical links are attractive particularly when using laser beams because the radiated energy can be confined to a small solid angle. This avoids spectrum crowding and allows the transmitted signal to be concentrated upon a smaller area than with conventional radio links. Optical paths through the atmosphere, however, are subject to attenuation by rain, fog, and other meterological conditions as well as interference by physical objects. In addition, atmospheric optical links cannot be bent around corners without the use of mirrors and prisms which introduce additional undesirable attenuation and light scattering.

Experiments have been conducted as noted in Ref. 2 with light pipes to contain optical beams generated by sources such as light emitting diodes and lasers. Since the pipe walls tended to scatter the light, it became necessary to keep the light away from the walls. This was accomplished by using either lenses or flowing gas. The pipes are large

in size, difficult to align, sensitive to temperature variations, and require additional lenses or optical devices for bending around corners. Installation of light pipes is expensive and they are costly to maintain.

An alternative is to use glass fibers as the transmission medium. Glass fibers are small, lightweight, and can be easily bent around corners without significantly degrading the transmitted signal. In theory, a light beam will be totally confined inside a glass cylinder by total reflection if

$$n_a \operatorname{Sin} \theta < \sqrt{n_g^2 - n_a^2} \quad ,$$

where n_g is the refractive index of the glass fiber, n_a is the refractive index of air ($n_a = 1.00$), and θ is acceptance angle, the angle between the incident light vector and the axis of the glass fiber. Minute irregularities such as dust particles at the air-glass interface will result in scattering of the light and attenuation of the signal. This scattering can be eliminated by cladding the glass fiber with a material having a lower index of refraction than the fiber. If this cladding is several wavelengths thick, light will propagate in the fiber and cladding and will not contact the cladding-air interface. The technology of manufacturing fiber optic cables is advancing rapidly and fibers can be produced in which the radius is accurately controlled from a few to several hundred microns.

The cladding material used to prevent undesired signal attenuation also serves to prevent external radiation from being induced into the fiber material. An additional advantage of the cladding, then, is that

cross talk between fibers and electromagnetic interference are for all practical purposes, totally eliminated. Since there is no electrical connection between the ends of the fiber, ground loops, short circuits, and isolation problems are also eliminated. Fiber optic lines are smaller, lighter in weight, more flexible, and have a higher thermal resistance to heat than do conventional transmission lines. Since the fiber bundle is smaller than conventional media, terminal connectors are smaller and miniaturization of equipment and patch panels is made easier.

Attenuation of the transmitted light through glass fibers can range up to 1000 decibels per kilometer. A great deal of research effort and technology has gone into the production of low loss glass fibers. Some companies are producing fibers with losses in the vicinity of 20 db/km and lower [Ref. 4]. The use of these low loss fibers then makes the possibility of signal transmission via a fiber optic link both attractive and feasible although at present, the cost of these low loss fibers is relatively high. Even with the presently available high loss fibers, signal transmission over relatively short lengths is feasible and with optical repeaters in the link, greater distances can be obtained.

Losses in glass fibers are caused by impurities and non uniformities in the refractive index of the material. It is therefore necessary to maintain a high level of purity in the manufacturing process. It has been estimated in Ref. 2 that to achieve a loss of 20 db/km, that impurity concentrations must be less than one part in 10^7.

There are two basic types of optical fibers, single mode and multi mode. Whether the fiber is single or multi mode is dependent upon a

parameter of the fiber known as the step refractive index. This parameter is defined as

$$V = \frac{2\sqrt{2r}}{\lambda}(\bar{n}\Delta n)^{\frac{1}{2}} ,$$

where r is the core radius, λ is the free space wavelength, $\bar{n}$ is the average refractive index of core and cladding, and Δn is the difference in refractive index between cladding and core. For a step refractive index, V, below about 2.4, only the lowest order mode will propagate through the fiber. For values of V greater than 2.4, additional modes will propagate. The number of modes that will propagate through the fiber is approximately $V^2/2$.

The single mode fiber is capable of propagating only one waveguide mode but with low pulse distortion and wide information transfer bandwidth. In a single mode fiber, it is not possible to combine a large acceptance angle with large core area. Multi mode fibers can combine large core areas with large acceptance angles and will propagate more than one mode, however, this is at the sacrifice of about two orders of magnitude of bandwidth as compared to the single mode fiber [Ref. 2]. The bandwidth of a single mode fiber is proportional to the reciprocal of the square root of the fiber length while the bandwidth of multi mode fibers is proportional to the reciprocal of the length.

The best transmission characteristics of fiber optic lines to date has been obtained in the infrared region of the electromagnetic spectrum [Ref. 5]. Light emitting diodes and photodiodes in the infrared are commercially available and readily obtainable. In theory, then, it is possible to couple a modulated infrared LED, an optical fiber, and an

infrared photodetector and obtain a signal transmission system which is reasonably efficient as long as the characteristics of the individual components are suitably matched in spectral response, light intensity, and responsivity of the photo detector.

C. PHOTODETECTOR CHARACTERISTICS AND PROPERTIES

Commercially available optical detectors suitable for use in a fiber optic communication system offer several distinct advantages. They are small, lightweight, have low power consumption, and offer high sensitivity and fast response. They generally require no special cooling and are easily coupled to an optical fiber. Photodetectors produce an electrical output signal which is proportional to the intensity of light incident upon the sensitive element. A photon, or a quanta of radiant energy, can transfer its energy to an electron in the detector material. If the energy imparted to the electron is sufficient, the electron may escape from the surface of the material. This is known as the photoelectric or photoemissive effect [Ref. 6] and is an external effect. There are also a number of internal photoeffects in which the electron may be raised from a nonconducting to a conducting state and in so doing, producing a charge carrier. The type of charge carrier is determined by the characteristics of the semiconductor material. Biasing the detector will produce an electric field which causes changes in the number of charge carriers which then causes the current flowing in the detector to be varied. This is known as the photoconductive effect.

If an electron hole pair is produced by a photon in the vicinity of a p-n junction, the electric field across the junction will separate

the carriers and produce a photovoltage. This is known as the photovoltaic effect. Since the bias is effectively supplied by the junction, no external bias is required.

The energy of a photon is proportional to its frequency and is given by

$$E = h\nu \quad ,$$

where h is the proportionality constant known as Planck's constant and ν is the frequency of the photon. When a photon collides with an electron, and its energy is transferred to the electron, the electron may have sufficient energy to escape from the surface of the material. The amount of energy required for the electron to escape is known as the work function, ϕ, and is a characteristic of the material. Since the energy of the photon is dependent upon frequency, there is a low frequency or long wavelength limit beyond which the energy is insufficient to reject an electron. This is known as the cutoff wavelength and is defined by

$$\lambda_c = \frac{1.24}{\phi} \quad ,$$

where ϕ is in electron volts, and λ_c is in microns.

In a semiconductor, valence band electrons can be excited into the conduction band but not without traversing what is known as the forbidden energy band. Hence, for conduction to take place, the electron must have sufficient energy to overcome this forbidden energy gap, E_g. As with photoelectronic devices, there is a long wavelength cutoff defined

as

$$\lambda_c = \frac{1.24}{E_g} ,$$

where λ_c is in microns and E_g is the band gap energy expressed in electron volts. This band gap energy is also a characteristic of the semiconductor material. Silicon is a common semiconductor photodetector material and has a band gap energy of 1.12 eV at 300°K. Pure silicon then has a cutoff wavelength of 1.107 microns which corresponds to a cutoff frequency of approximately 3×10^{14} hertz. Doping the semiconductor material with impurities or cooling it will cause the band gap energy to decrease with a subsequent increase in the cutoff wavelength. Photodetectors are readily available which are responsive at infrared wavelengths and they are relatively inexpensive.

Optical detectors which are useful in fiber optic communication systems are considered to be square law devices in which the output current of the detector is proportional to the square of the electric field in the optical wave averaged over the area of the detector surface. In a direct detection system, the carrier is intensity modulated and the output current, I, of the photodetector due to the optical signal is

$$I = \frac{eqPG}{h\nu} ,$$

where e is the electronic charge, q is the quantum efficiency of the detector, P is the optical power incident upon the detector, G is the internal gain, and $h\nu$ is the energy of a photon. In addition to signal

current, noise generated internally inside the detector will also produce an output current. Noise currents are due primarily to shot noise and thermal noise. Shot noise is caused by statistical fluctuations in the rate at which current is generated in the detector and thermal noise is due to fluctuations in the junction temperature.

Noise current is called dark current and represents the lower limit at which an output signal can be detected. The signal to noise power ratio can be shown to be

$$\frac{S}{N} = \frac{I_s^{\,2}}{2e(I_s + I_d)GB + \frac{4kTB}{R}}$$

as shown in Ref. 2 where I_s is signal current, I_d is dark current, e is the electronic charge, GB is gain-bandwidth product of the detector, k is Boltzmann's constant, and T is temperature in degrees Kelvin.

Perhaps the simplest description of detector performance is its responsivity. Responsivity is normally given in terms of output voltage or current per watt of power incident upon the active surface of the detector. Other considerations to be taken into account when selecting a detector are frequency response and dark current, or noise output.

III. EXPERIMENTAL LAYOUT

One of the primary considerations in the design and construction of the system was that the components utilized be readily available commercial components. Other prime considerations were that the design be kept as simple as possible and that cost be kept within reasonable limits.

On the basis of considerations discussed in the background material, it was determined that the infrared region of the spectrum would be the most reasonable and feasible to use. Devices that perform best in this region are easily obtainable and match the characteristics of the fiber optics ideally.

The procedure followed in the design of the system was to select an infrared light emitting diode and a modulating circuit and then, a photo-detector unit in the infrared region which would satisfy the requirements of the system.

A. MODULATOR

The light emitting diode selected for use was the Motorola MLED930. The response curve of this device, Figure 1, peaks at 9000 Angstroms and an excellent trade off between drive current required to operate the device and light output is realized. The device is capable of conducting 80 milliamperes of current continuously without damaging the diode. The diode is also capable of providing 550 microwatts of light output with a drive current of 50 milliamperes and will produce 120 microwatts of light output with a drive current of 10 milliamperes. The forward resistance of the device varies from 12.3 ohms at a current of 100 milliamperes to 150 ohms at a drive current of 60 microamperes.

In order to protect the diode, it was decided to operate it at a forward current of approximately one half of the rated current, in the vicinity of 40 milliamperes. At this current, the forward resistance of the diode was measured as 34 ohms.

It was decided that a simple one stage transistor amplifier circuit could be utilized as the modulator and that this would effectively provide a current varying output from a voltage driven input. The transistor selected as the amplifier was the 2N3252 high power switching transistor. Because of the desired wide bandwidth characteristics of the system, a high gain-bandwidth is required. The 2N3252 is capable of a gain-bandwidth product of 200 million and is capable of providing the current gain sufficient to drive the light emitting diode. The output characteristics of the 2N3252 are illustrated in Figure 2.

The modulator circuit selected for use was that of a simple self biased amplifier shown in Figure 3. Selection of a supply voltage of 10 volts and an output current of approximately 40 milliamperes requires a resistance of 250 ohms in the output circuit. Selecting an operating point at a V_{ce} of approximately five volts and a collector current of 40 milliamperes results in a base current of approximately .34 milliamperes according to the output curves. Assuming that collector current and emitter current are approximately equal, and with a diode forward resistance of 34 ohms and an emitter resistor of 60 ohms, an emitter voltage of 3.4 volts is obtained. Base to emitter voltage in a silicon transistor is approximately .6 volt, hence the base voltage on the amplifier is approximately 4 volts. The equivalent base resistance, R_b, is equal to the parallel combination of R_1 and R_2. For proper biasing, R_b should be at least ten times the value of the resistance in the emitter

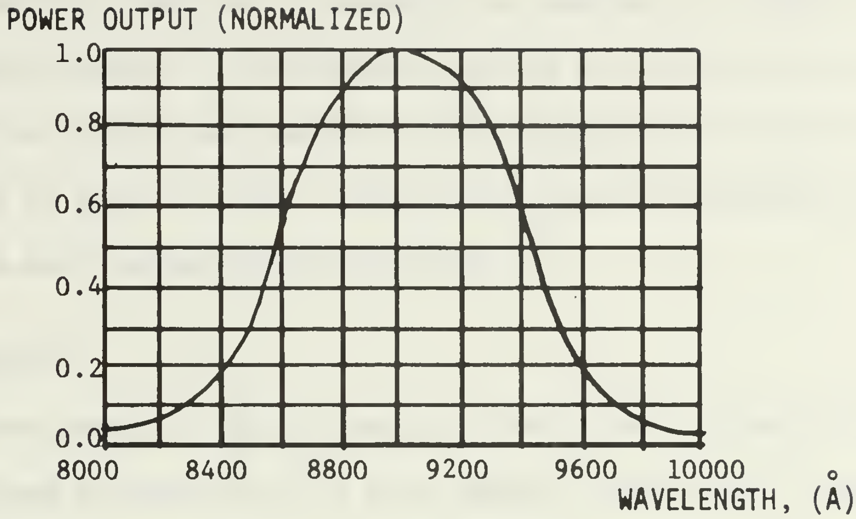


FIGURE 1

OUTPUT CHARACTERISTICS OF MLED930

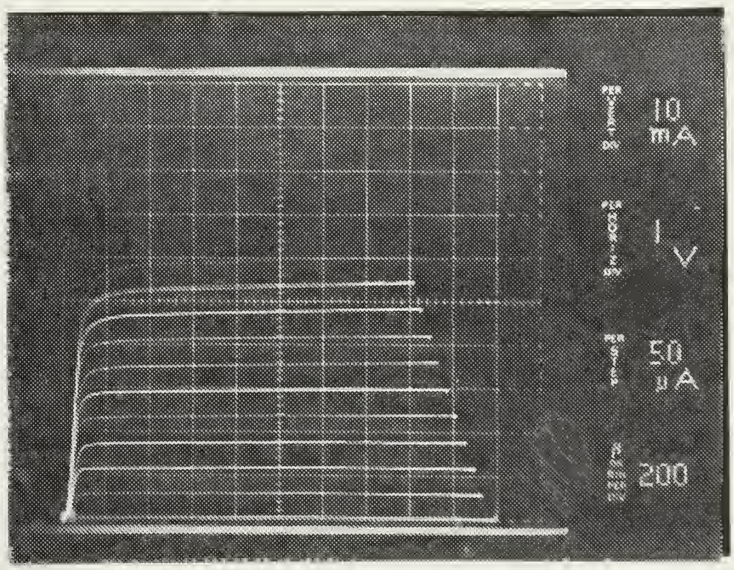


FIGURE 2

OUTPUT CHARACTERISTICS OF 2N3252

circuit or at least 940 ohms. The values chosen for R_1 and R_2 result in a parallel combination of 2.2 Kilohms which meets the above requirement. Careful selection of resistors was necessary in order to obtain the required values. The modulator circuit was constructed on a printed circuit board layout and enclosed in an aluminum case with a BNC input connector in order to reduce undesirable spurious radiations and to present a neat compact appearance [Fig. 4].

B. DETECTOR

The unit selected for the detector device was the MDF 428 model manufactured by Meret Inc., of Santa Monica, California. This device is a photo-detector and preamplifier combination enclosed in a TO-5 configured case. The MDF 428 is capable of light detection and signal amplification from zero to fifty Megahertz and has a responsitivity in excess of 4.0 millivolts per microwatt of input at a wavelength of 9000 Angstroms (Figure 5). RMS noise voltage output of the device is less than 100 microvolts. Device power supply requirements are 6 volts at 3 milliamperes B+ and a negative 30 volt supply to provide bias for the photodetector. The manufacturer's suggested circuit for connecting the unit was utilized and appears in Figure 6. As in the case of the modulator circuit, the photodetector unit was mounted in an aluminum case with a BNC output connector as shown in Figure 7 in order to prevent spurious radiation from being induced into the system.

The complete system including power supplies, a Wavetek model 142 signal generator, Tektronix model 422 oscilloscope to monitor output of the photodetector, and fiber optics is shown in Figure 8.

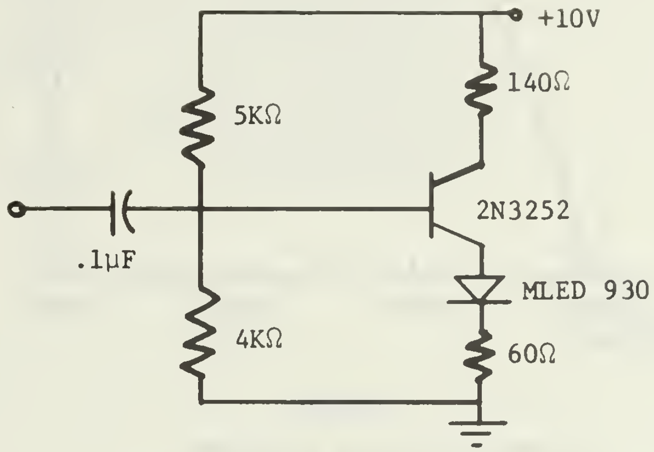


FIGURE 3

MODULATOR CIRCUIT

FIGURE 4

MODULATOR UNIT

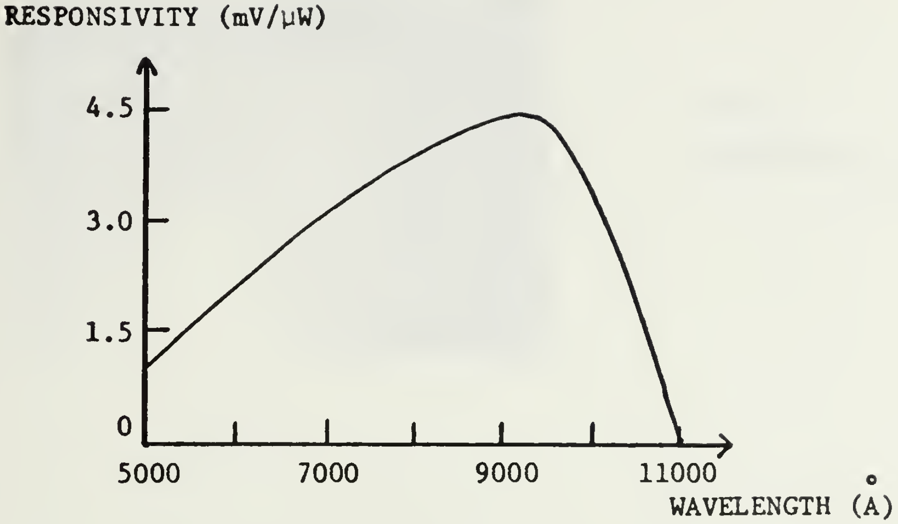


FIGURE 5

RESPONSE CURVE OF MDF428

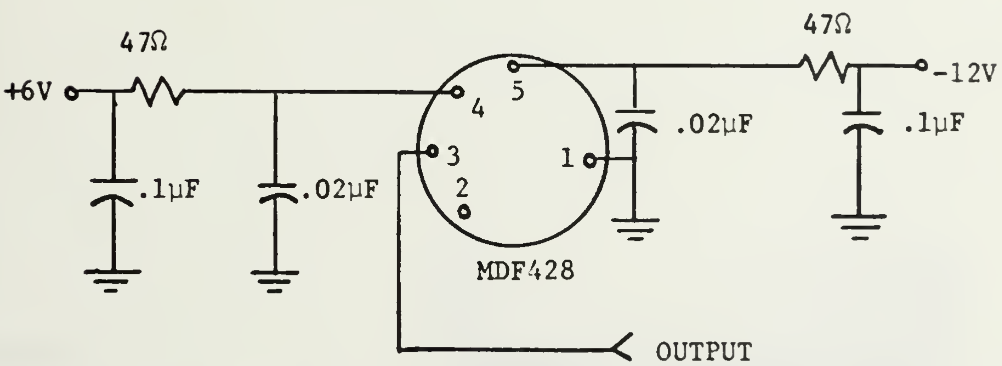
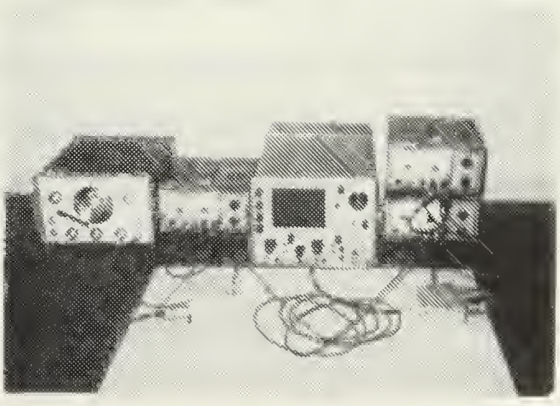


FIGURE 6

PHOTODETECTOR CIRCUIT

FIGURE 7
PHOTODETECTOR UNIT

FIGURE 8
FIBER OPTIC INFORMATION TRANSFER SYSTEM



IV. EXPERIMENTAL PROCEDURE

The complete system was tested to determine its performance and its applicability as an information transfer system. Analysis of the following areas was conducted: 1) frequency response, 2) minimum discernible signal, 3) saturation level, 4) linear dynamic range, 5) noise figure, and 6) spectrum analysis.

A. FREQUENCY RESPONSE

Results obtained upon conducting tests of frequency response indicated that the 3 dB bandwidth of the system was 8.3 kilohertz to 6.8 megahertz. Analysis of frequency response and all other areas of investigation then, were restricted to the frequency range of 1 kilohertz to 10 megahertz. Examination of the frequency response was conducted by utilizing a constant voltage input to the system which was obtained from the Wavetek 142 signal generator with a sinusoidal output. The input signal reference level was set at 150 millivolts peak to peak. Maximum output voltage level was determined to be one millivolt peak to peak at the mid-range of the output curve. All voltage readings obtained were measured with a Tektronics model 422 oscilloscope and were the peak to peak values. The output response curve is shown in Figure 9. It is observed from this curve that the response is very flat over the mid-range of the output and that the upper and lower 3dB points, where output voltage falls below .707 of the maximum value, are at 8.3 kilohertz and 6.8 megahertz respectively.

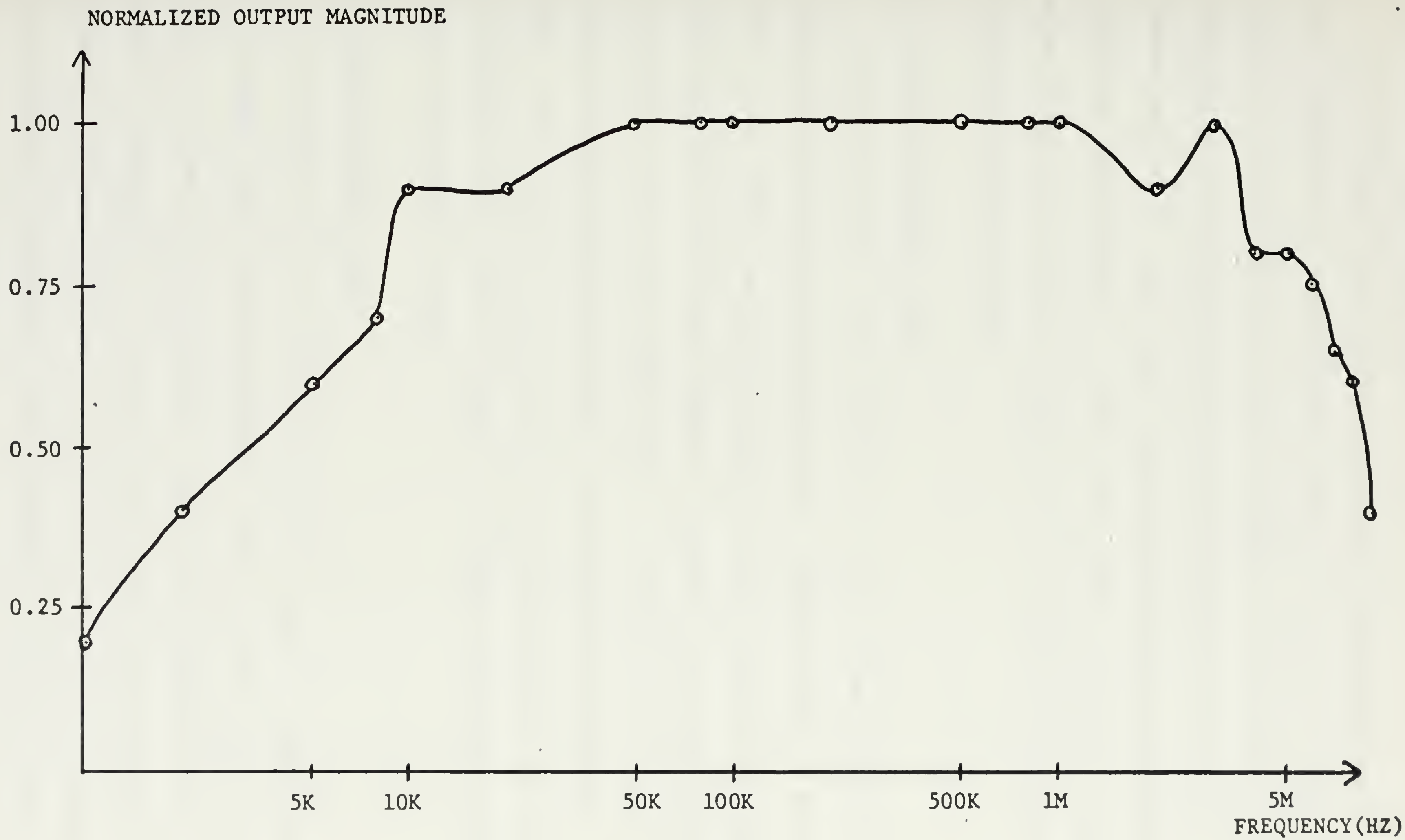


FIGURE 9

FREQUENCY RESPONSE

B. MINIMUM DISCERNIBLE SIGNAL

An analysis of minimum discernible signal level was conducted over the frequency range of interest by means of observing the output of the system on the most sensitive scale settings of the Tektronics 422 oscilloscope, and increasing the system input until the signal just became observable at the output. The sinusoidal peak to peak input signal was then measured. A plot of the minimum discernible signal versus frequency is shown in Figure 10. The value was typically 5 to 10 millivolts peak to peak.

C. SYSTEM SATURATION LEVEL

The input voltage level at which the output became saturated or distorted was measured across the useful frequency range of the system. Input to the system was again a sinusoidal input from the Wavetek 142 signal generator and system output was observed on the Tektronix 422 oscilloscope. The input signal level was increased to the point at which the output signal just began to show signs of distortion. The input level at which distortion occurred was then plotted as a function of frequency and is shown in Figure 11. Typical saturation levels were 2½ to 3 volts peak to peak.

D. LINEAR DYNAMIC RANGE

The dynamic range over which the system reacts in a linear manner to the input signal can be resolved by comparing the results of the analyses of the minimum discernible signal and saturation level tests conducted previously. The linear dynamic range can be obtained from observing the range of output voltage levels over which the signal is discernible over system noise and is undistorted. Once the output

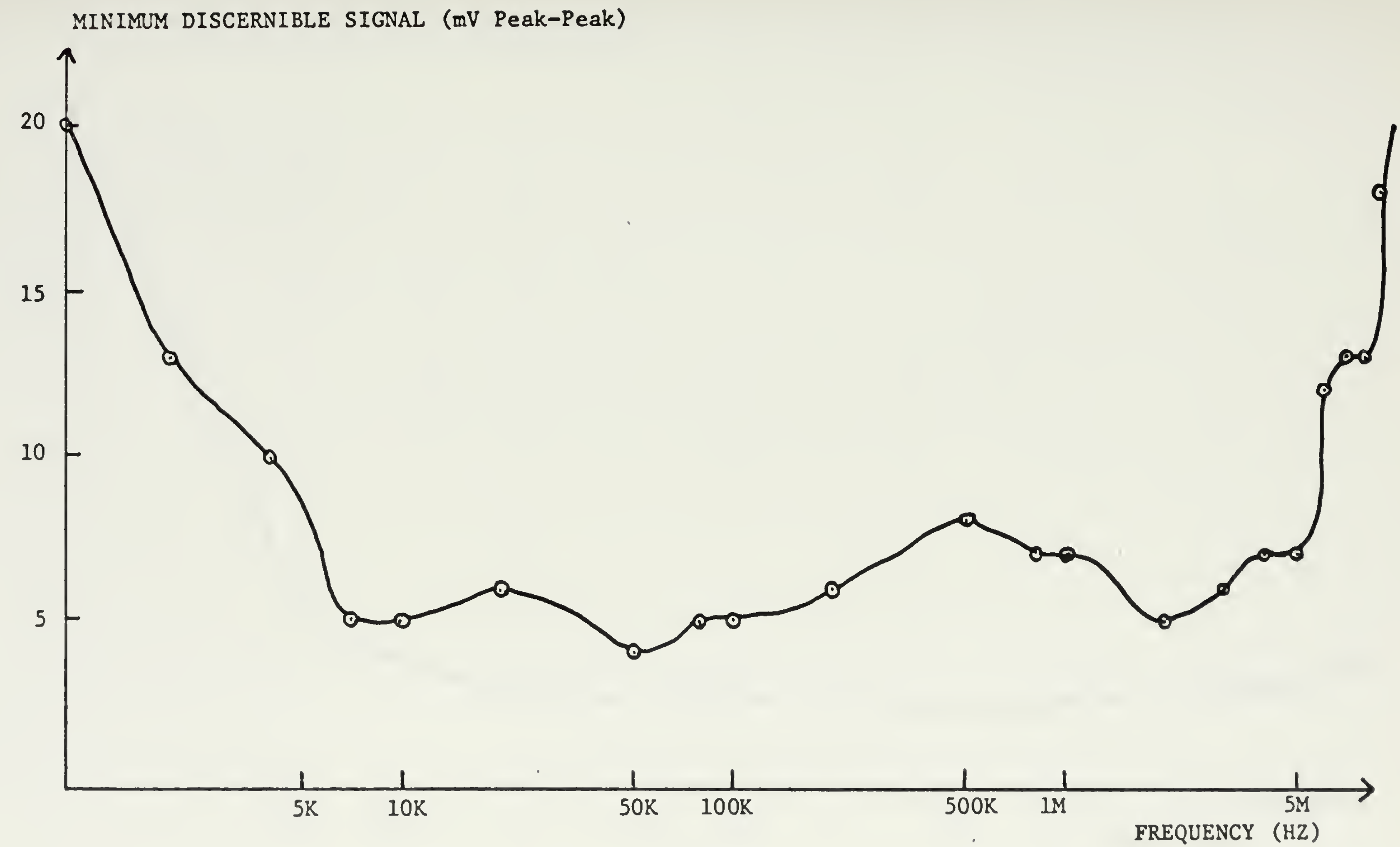


FIGURE 10

MINIMUM DISCERNIBLE SIGNAL

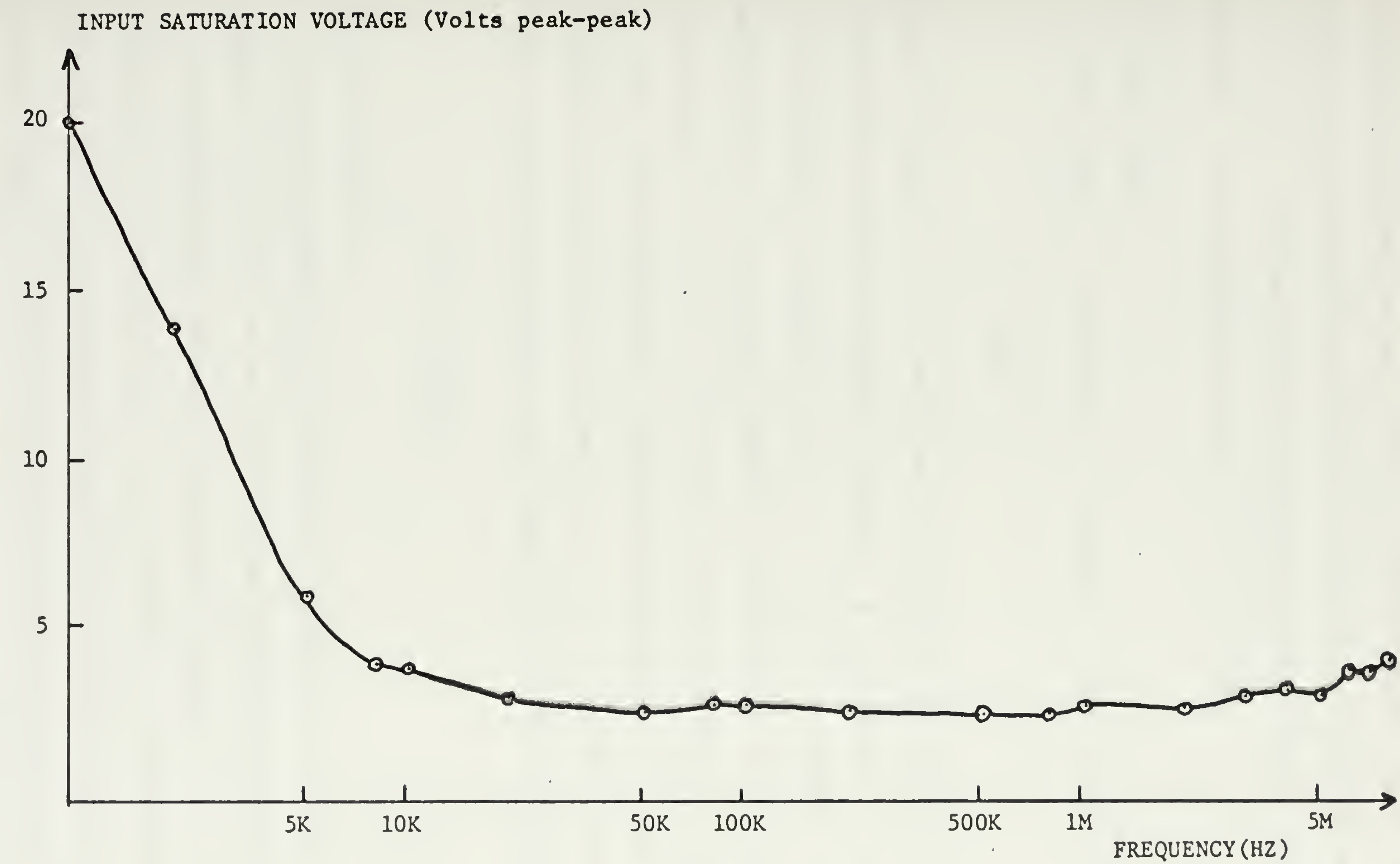


FIGURE 11

SATURATION LEVELS

signal becomes distorted, the system is no longer operating linearly. Determining the range between MDS and saturation voltage levels in decibels and plotting these values as a function of frequency results in the curve of Figure 12 which indicates the linear dynamic range of the system. Mid band dynamic range was 50 to 55 dB.

E. NOISE FIGURE

Noise figure of a system can be obtained from the relationship

$$N_o = kTBFG \tag{1}$$

[Ref. 7], where N_o is the noise power output when the system input is terminated in its characteristic impedance, k is Boltzmann's constant, T is temperature in degrees Kelvin ($kT = 4 \times 10^{-21}$ Watts/sec at room temperature), B is the noise bandwidth of the system, G is the maximum power gain of the system, and F is the system noise factor. Since kT is known at room temperature, B and G can be measured and N_o can be measured, it is possible to solve for F, the only unknown. Once F is known, it can be converted to noise figure, NF, by the relationship

$$NF = 10\log_{10}F \tag{2}$$

as noted in Ref. 7.

The input impedance of the system was measured as 42.8 ohms. Using a decade box resistor set at this value and measuring the system output on a true RMS reading voltmeter with an input impedance of 50 ohms, resulted in a true RMS voltage of .09 microvolts. This reading was obtained on the most sensitive scale of the instrument and was subject to some variation and interpolation between scale markers and is therefore subject to some ambiguity. Using the relationship that power is

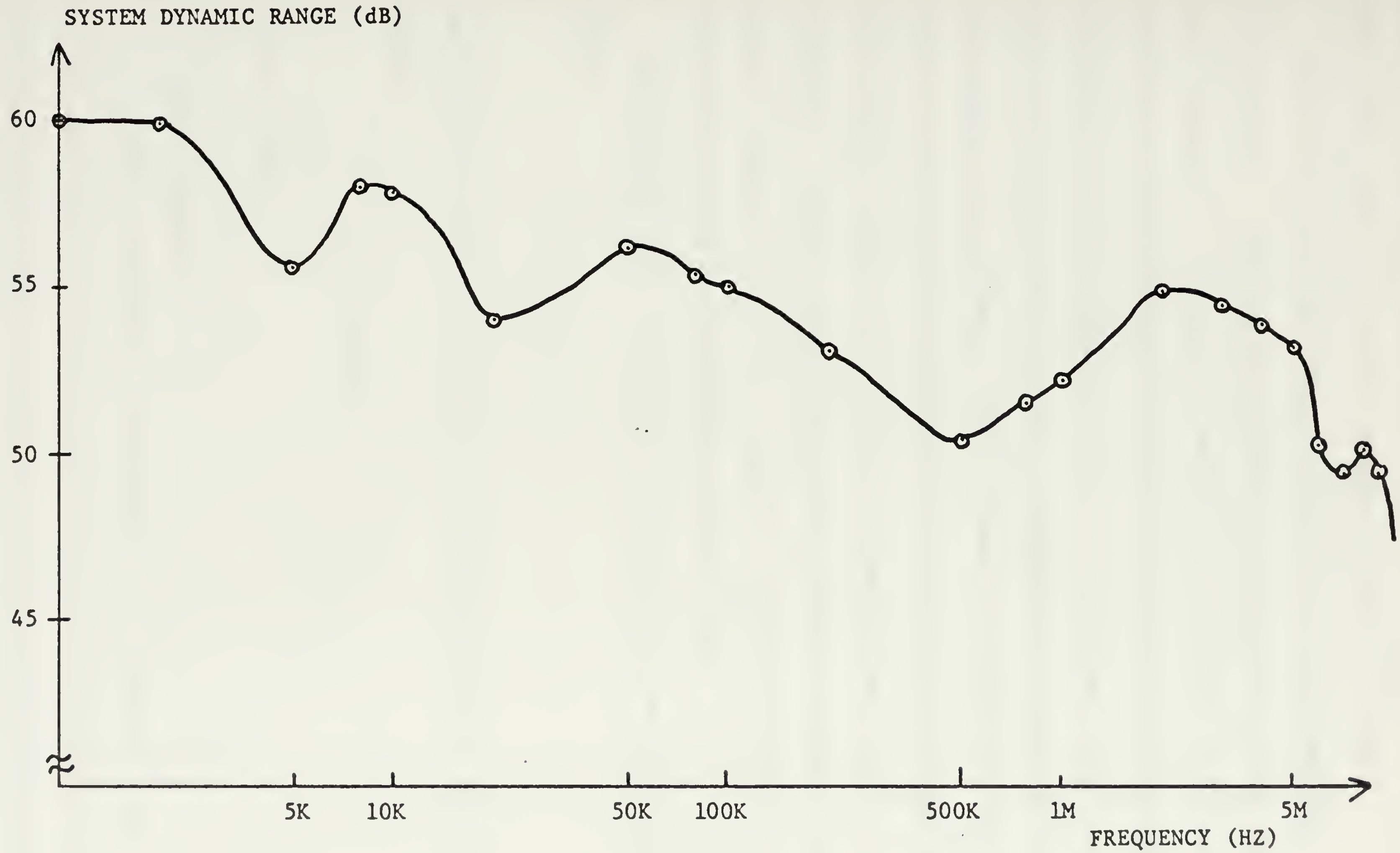


FIGURE 12

LINEAR DYNAMIC RANGE VS. FREQUENCY

equal to the square of the voltage divided by the resistance, the noise power output, N_o, was obtained as 1.67×10^{-16} watts.

The next step was to obtain a value for the gain-bandwidth product of the system. This was accomplished by plotting the system power gain as a function of frequency and performing a graphical integration technique to determine the area under the curve. This area then, represents the gain-bandwidth product of the system. Obtaining the input and output power levels was accomplished by measuring the root mean square voltage levels, squaring them, and dividing by the load impedance into which they were fed. Upon obtaining the input and output power levels, a ratio can be taken to determine power gain at a given frequency. A plot of power gain versus frequency obtained in this manner is shown in Figure 13. Graphical integration applied to this curve results in a gain-bandwidth product of 195.

The noise factor, F, was then calculated with the aid of equation (1) as

$$F = 21.3 \quad .$$

Converting this value according to equation (2) resulted in a noise figure,

$$NF = 13.28 \text{ dB}$$

for the system.

F. SPECTRUM ANALYSIS

An analysis of the level of harmonics of the input signals present at the output and of spurious signals generated within the system was conducted with the aid of a Tektronix 551 dual beam oscilloscope and the

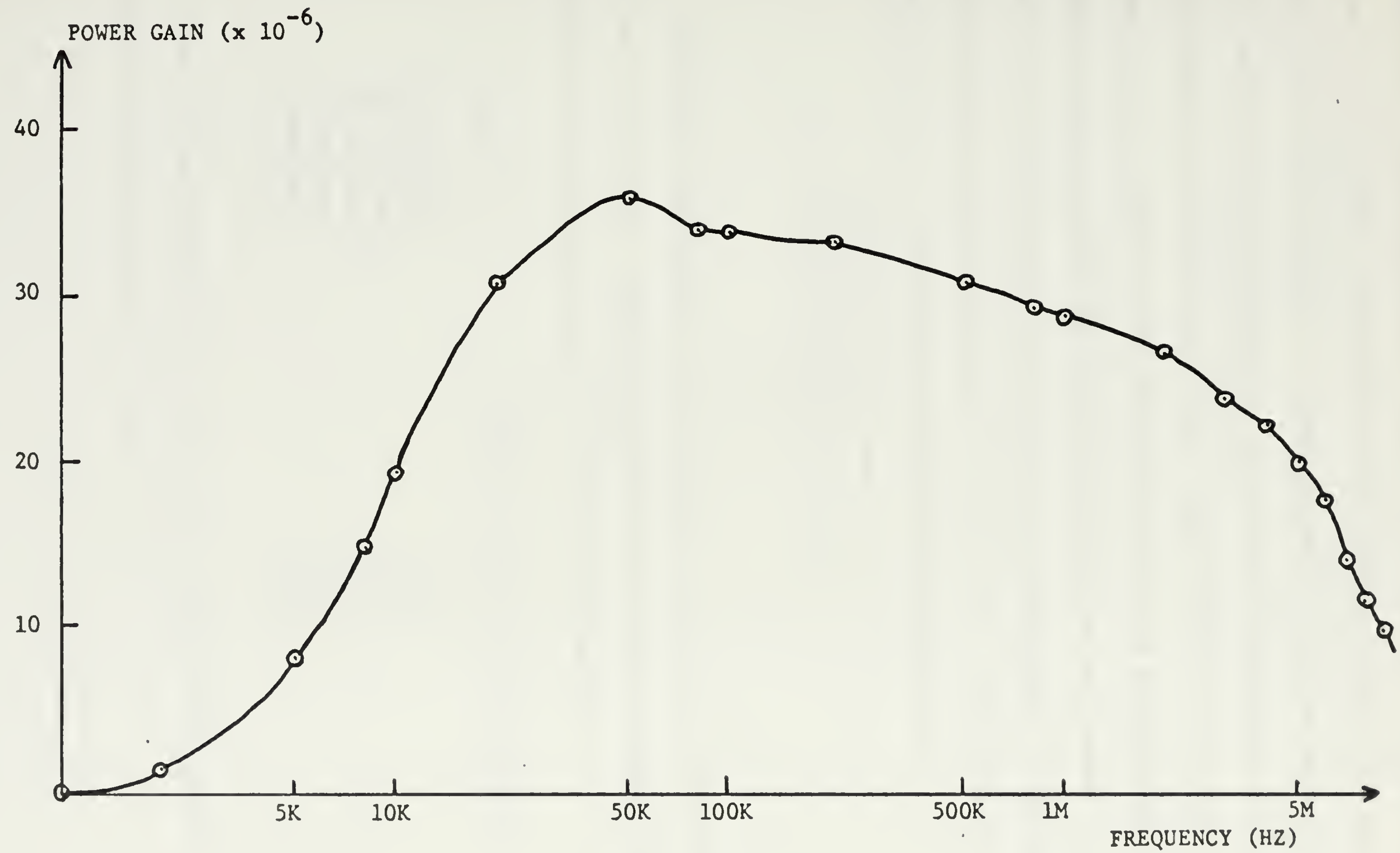


FIGURE 13

SYSTEM POWER GAIN VS. FREQUENCY

Tektronix 1L5 and 1L10 spectrum analysis plug-in units. Single sinusoidal voltage inputs were applied to the system at several frequencies within the range of interest. Output harmonic amplitudes were measured and compared with the fundamental. This test was conducted at each of the frequencies for both normal input signal levels and for input signals large enough to cause output distortion. A ten kilohertz signal at 100 millivolts RMS amplitude was applied and harmonics were observed at 30 kilohertz (3.8 millivolts RMS amplitude), 50 kilohertz (6 millivolts), and 60 kilohertz (4.5 millivolts). Total harmonic distortion can be determined by the relationship [Ref. 8]

$$D = \frac{\sqrt{A_2^2 + A_3^2 + A_4^2 + \ldots} \times 100.}{A_1}$$

Using this relationship, total harmonic distortion at 10 kilohertz is seen to be 8.41%. Similar measurements were taken throughout the frequency range of the system with the following results:

Frequency	Harmonic distortion (percentage)
10 kilohertz	8.41
50 kilohertz	1.35
100 kilohertz	2.64
500 kilohertz	2.55
1 megahertz	6.25
5 megahertz	0.00
8 megahertz	0.75.

The same measurements were taken with an input large enough to cause output distortion with the following results:

Frequency	Harmonic distortion (percentage)
10 kilohertz	18.57
50 kilohertz	18.60
100 kilohertz	26.85
500 kilohertz	15.60
1 megahertz	7.00
5 megahertz	25.09
8 megahertz	12.00.

It can be seen from these values that the harmonic distortion increases significantly when the system is overdriven.

Two separate sinusoidal signals were then applied simultaneously to the system in order to determine the amount of distortion due to intermodulation as well as harmonics. With input signals of 50 kilohertz and 80 kilohertz applied together, each with RMS amplitude of 1 volt, no harmonics or other intermodulations were observed at the output. The same results were obtained with inputs at 100 kilohertz and 400 kilohertz applied simultaneously with RMS amplitudes of one millivolt each. In both cases noted above, the only signals observed at the output were the two fundamental frequencies applied. A spectrum analysis of the input in both cases resulted in some harmonic and intermodulation distortion but this was too weak to appear at the output of the system.

With simultaneous inputs at one megahertz and four megahertz applied, no harmonic or intermodulation distortion at the output was observed due to the input, however, some very low level spurious responses were observed in the vicinity of 1.04 to 2.27 megahertz even with the input disconnected. These signals were also present when the optical fiber was disconnected from the modulator, hence it was determined that these signals were generated within the detector and power supply circuitry. Minor redesign or filtering may be required in order to reduce these spurious responses to an acceptable level.

V. CONCLUSIONS

Of the two primary applications originally considered for the system, fiber optic interconnection between a radio receiver and tape recorder, and a link between receiving antennas and receivers in the 2 to 32 megahertz range, the first application appears to be the more readily attainable. Frequency response limitations of this system design at the present time preclude its being used in the 2 to 32 megahertz range.

State of the art tape recording systems require a dynamic range on the order of 25 to 30 dB and various frequency response ranges depending upon the application [Ref. 9]. The observed dynamic range of this system meets these requirements and as long as frequency response requirements are restricted to the range of about 7 kilohertz to 7 megahertz, tape recorder requirements are met. Current linear state of the art recorder response at 120 inches per second is 2.5 megahertz. Improved modulator and detector circuit designs could conceivably upgrade system performance to the point at which all tape recorder requirements, particularly at lower frequencies could be met.

Even though the antenna to radio receiver link requirements were not met, it has been demonstrated that the concept is a valid one and that analog signals can be transmitted via fiber optic links in an efficient manner. In this application also, it is felt that an improved design of the modulator and detector circuits would significantly increase the range of frequency response particularly since pure Gallium Arsenide light emitting diodes with diffused junctions can theoretically be modulated at rates in the vicinity of 50 megahertz. Other semiconductor materials are capable of higher rates of modulation at different wavelengths than those

of Gallium Arsenide. The photodetector used in the system is capable of detection of signals modulated at rates up to 50 megahertz, however, other commercial photodetectors are capable of handling rates in excess of 100 megahertz with response times in the nanosecond range.

The fiber optic bundle utilized (Corning type #5011) is priced at approximately $.30 per foot in custom finished lengths. A length of ten feet of the material was utilized at a cost of approximately $3.00. The cost of the modulator including the light emitting diode was approximately $13.00 and the detector unit is priced at $200.00. Total system cost was approximately $220.00 and could concievably be lower if the individual components were to be purchased in large quantitites or if other suitable components could be obtained at lesser prices.

LIST OF REFERENCES

1. IBM Electronic System Center Final Report, High-Speed Optical Data Link for Interconnection Between LSI Modules, by A. D. Damari, H. H. Bloem, D. J. Stigliani, Jr., R. C. Clapper, and H. C. Farrel, p. 1-2, April 1973.

2. Naval Electronics Laboratory Center Report 1763, Transfer of Information On Naval Vessels Via Fiber Optics Transmission Lines, by H. F. Taylor, p. 6-22, 1 January 1972.

3. Sze, S. M., Physics of Semiconductor Devices, p. 58, Wiley, 1969.

4. Kapron, F. P. et al, "Radiation Losses in Glass Optical Waveguides," Applied Physics Letters, v. 17, p. 423, 1970.

5. Montrose, C. J., and Macedo, P. B., "Glass Fiber Optical Waveguides for Laser Communications Systems," Naval Research Reviews, v. 26, p. 32, January 1973.

6. Hudson, R. D., Jr., Infrared System Engineering, p. 276, Wiley, 1969.

7. Skolnik, M. I., Introduction to Radar Systems, p. 363, McGraw-Hill, 1969.

8. Ryder, J. D., Electronic Fundamentals and Applications, p. 365, Prentice-Hall, 1970.

9. Hewlett Packard Application Note 89, Magnetic Tape Recording Handbook, by J. A. Howard and L. N. Ferguson, p. 2-7, August 1967.

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State of the art advances in fiber optics have reached the point at which modulated light signals can be transmitted by means of a fiber optic bundle and subsequently detected. A system capable of modulating a light emitting diode with wide band analog signals, transmission through a fiber optic bundle, and subsequent detection is investigated.

Tests are conducted to determine frequency response, linear dynamic range, saturation levels, minimum discernible signal, noise figure, and spectrum

(20.) continued

characteristics of the system.

As a result of the investigation, it is determined that the system is suitable for transmission of information to tape recorders from receiver systems and is capable of other analog information applications where signal frequencies do not exceed seven megahertz.

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